

Unintegrated sea quark at small x and vector boson production

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We discuss recent work on the transverse momentum dependent sea quark density and its application to forward Drell-Yan production.

1 Introduction

Scattering processes with a single hard scale are well described in QCD within the framework of collinear factorization. The treatment of multi-scale processes, on the other hand, is more involved. In this case, generalized factorization formulas are needed¹ to gain control over large logarithms in higher orders of perturbation theory. Such formulas typically involve transverse-momentum dependent (TMD), or “unintegrated”, parton distribution and parton decay functions. A broad class of multiple-scale events is given by small- x processes. These are one of the main sources of final states in the central region at the LHC, and lead to sizeable rates of forward jet production at the LHC^{2,3}. At small x , TMD parton distributions arise naturally as a consequence of high energy factorization and BFKL evolution⁴. k_T -factorization^{5,6} provides then the matching of these high energy factorized TMD distributions to collinear factorized distributions. For Monte Carlo applications a convenient description is given in terms of the CCFM evolution equation⁷ which interpolates for inclusive observables between DGLAP and BFKL evolution⁸. This therefore supplies a natural basis for a Monte-Carlo realization of k_T -factorization, such as that provided by the Monte Carlo event generator CASCADE⁹.

Computational tools based on TMD parton densities have so far been developed within a quenched approximation where only gluons and valence quarks are taken into account^{3,10}. While this captures correctly the leading contributions at small x , it is mandatory to go beyond this approximation in order to include preasymptotic effects and to treat final states associated with quark-initiated processes such as Drell-Yan production.

In this contribution we present work¹¹ in this direction, and its application to forward Drell-Yan production. For further detail we refer to^{11,12}.

2 Definition of a TMD sea quark distribution and off-shell $qq^* \rightarrow Z$ coefficient

The unintegrated sea-quark distribution is analyzed in ¹¹ to logarithmic accuracy $\alpha_s(\alpha_s \ln x)^n$ based on the off-shell TMD gluon-to-quark splitting function ⁶. This is obtained by generalizing the expansion in two-particle irreducible kernels of ¹³ to finite transverse momenta, and reads

$$P_{qg}\left(z, \frac{\mathbf{k}^2}{\Delta^2}\right) = T_R \left(\frac{\Delta^2}{\Delta^2 + z(1-z)\mathbf{k}^2} \right)^2 \left[(1-z)^2 + z^2 + 4z^2(1-z)^2 \frac{\mathbf{k}^2}{\Delta^2} \right]. \quad (1)$$

Here $\Delta = \mathbf{q} - z \cdot \mathbf{k}$ with \mathbf{k} and \mathbf{q} transverse momenta of the off-shell gluon and quark respectively, while z is the fraction of the ‘minus’ light cone momentum of the gluon which is carried on by the t -channel quark. Although evaluated off-shell, the splitting probability is universal. Once combined with the gluon Green’s function, it takes into account the small x enhanced transverse momentum dependence to all orders in the strong coupling. In this approach the transverse momentum of the sea quark arises as a consequence of subsequent branchings at small x , with no strong ordering in their transverse momenta.

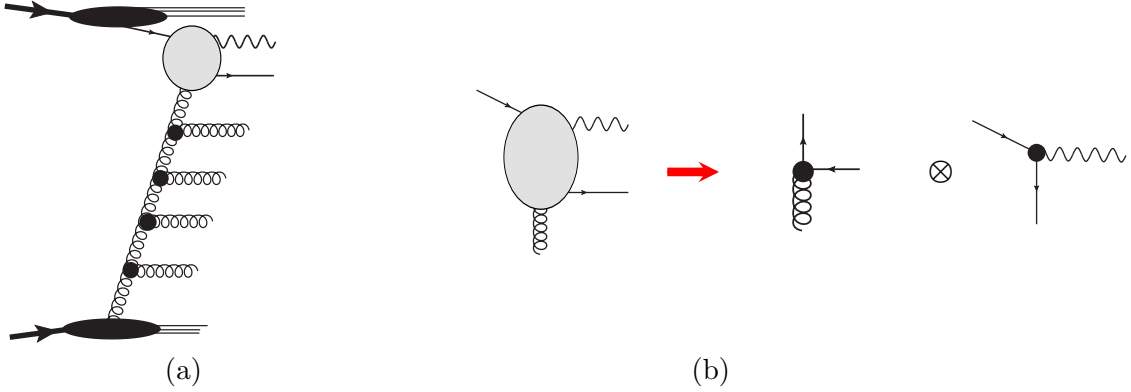


Figure 1: (a): If the vector boson is produced in the forward region, the sea quark density becomes sensitive to multiple small x enhanced gluon emissions, leading to a k_T -dependent gluon density (b): Schematic factorization of the partonic $qq^* \rightarrow Zq$ process of a) into the $g^* \rightarrow q^*$ splitting and the $qq^* \rightarrow Z$ coefficient.

To relate this parton splitting kernel to forward vector boson production, we analyze the flavor exchange process $g^*q \rightarrow Zq$, see Fig. 1. At high (partonic) center of mass energy, this process can be treated according to the ‘‘reggeized quark’’ calculus ^{14,15}. The latter extends the effective action formalism ¹⁶, currently explored at NLO ¹⁷, to amplitudes with quark exchange in terms of effective degrees of freedom, the so-called reggeized quarks ^{18,19}. The use of the effective vertices ^{14,15} ensures gauge invariance of the coefficients relevant to perform the high-energy factorization ^{5,6} for vector boson production, despite the off-shell parton.

If taken literally, the reggeized quark calculus leads for the $g^*q \rightarrow Zq$ process to a rather crude approximation to the $g^* \rightarrow q^*$ splitting function, associated with the lightcone momentum ordering condition which sets the ‘plus’ momenta of the off-shell quark for the $g^* \rightarrow q^*$ splitting to zero. For Eq. (1) this corresponds to the limit $z \rightarrow 0$. It is however possible ¹¹ to relax this kinematic restriction and to keep z finite, while maintaining the gauge invariance properties of the original vertex. For the $g^* \rightarrow q^*$ splitting this yields then precisely the splitting function Eq. (1).

On the other hand, in the $qq^* \rightarrow Z$ coefficient the high energy limit sets the ‘minus’ component of the quark momentum to zero. It proves to be possible to relax the ordering prescription also in this case. It is thus interesting to investigate the effect of these kinematic corrections, which are subleading in the collinear and high energy limits. In ¹¹ we express the off-shell

coefficient for the Z -boson cross section as

$$\hat{\sigma}_{qq^* \rightarrow Z} = \sqrt{2}G_F M_Z^2 (V_q^2 + A_q^2) \frac{\pi}{N_c} \delta(zx_1x_2s + T - M_Z^2). \quad (2)$$

Here the variable T parametrizes the off-shellness of the t -channel quark. In the collinear limit $T \rightarrow 0$ so that Eq. (2) agrees with the lowest order $qq \rightarrow Z$ coefficient. For the general off-shell case, T interpolates between the squared transverse momentum of the off-shell quark, if strong minus momentum ordering is fulfilled, and modulus of the four-momentum transfer, if this condition is relaxed. Correspondingly, the $qg^* \rightarrow qZ$ cross section is expressed in terms of convolutions in transverse momentum and four momentum transfer¹¹ respectively.

3 Numerical analysis

Fig. 2 shows a numerical comparison¹¹ of the factorized formulas discussed above with the $qg^* \rightarrow qZ$ matrix element result and with an expression which uses only the collinear splitting function. For small $|\Delta|$, the differences between t and k_T -factorized expressions are numerically

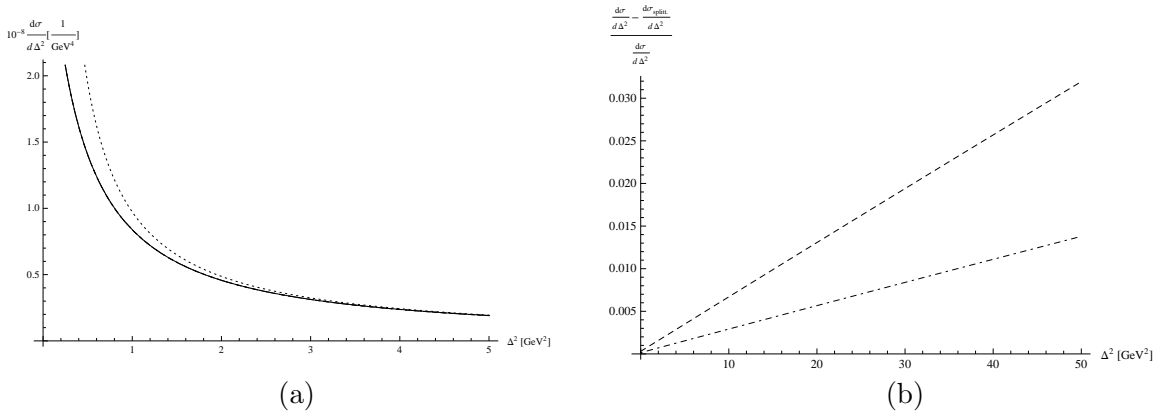


Figure 2: (a): Δ^2 dependence of the differential cross section $d\sigma/d\Delta^2$ for small $|\Delta|$: (solid) full; (dashed) no plus-momentum ordering; (dot-dashed) no plus-momentum and minus-momentum ordering; (dotted) collinear approximation. All but the last curve overlap in this region. We set $x_1x_2s = 2.5M_Z^2$, $k^2 = 2 \text{ GeV}^2$. (b): Relative deviations in the differential cross section $d\sigma/d\Delta^2$: (dashed) no plus-momentum ordering; (dot-dashed) no plus-momentum and minus-momentum ordering.

small, and both expressions are close to the full result; as $|\Delta|$ increases, we find that the deviations due to the kinematic contributions by which the two expressions differ become non-negligible, and that the t -factorized expression gives a better approximation to the full result.

Future extensions of the above results concern large- x contributions^{20,21,22,23,24,25}; parton shower Monte Carlo implementations¹²; inclusion of full quark emissions in the evolution, see²⁶ for related work in the context of next-to-leading order BFKL evolution.

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